Reliability Analysis to the Drift of Mega-Float Mooring System with a Break water

Masakatsu SAITO, Shunji KATO, Shigeo OHMATSU
Ship Research Institute, Ministry of Transport
6-38-1, Shinkawa, Mitaka, Tokyo 181-0004,Japan

1. Introduction

In Japan, the research with the aim of the practical application of the giant floating structure (VLFS) is advanced. VLFS with the object of this research is a thin and boxy floating body moored by large number of dolphins. That is about 5000m length, 1000m width, and it's behavior as an elastic body seems to be remarkable. Like the case in which it is utilized for airports, etc., there is a case in which breakwater is required in order to heighten working rate. This type of VLFS is called Mega-Float.

As a government agency, Ship Research Institute studies assessment method of the safety of VLFS, and especially, emphasizes the safety of the mooring system. The safety of the mooring system is defined as " the probability of the phenomenon, that the mooring system will be fractured and the floating body will be drifted out, does not happen in the fixed service life". This is the reliability. And, we shall call that phenomenon the failure.

Setting of the target reliability is necessary in order to assess quantitatively the safety of the mooring system of VLFS. Though it seems to decide target reliability by the depth of the relation for the society of the structure, the setting method has not been established still. The order of the reliability of mooring system designed by existing method seems to be the very important information for the establishment of the setting method of target reliability.

In this paper, the method for estimating the failure probability of mooring system, which moors boxy floating body of 5000m in the back of breakwater, in the storm is proposed. And, the following are reported : Order of the failure probability and sensitivity of the failure probability for the change of the design parameter.

2. Method for estimating failure probability

2.1 The definition of the failure probability

The drift of the floating body occurs by a collapse of the mooring system. With progressive collapse simulation of the multi-point mooring system by author and Yoshida et al., collapse time of the mooring system is very short under the condition in which the mooring device is fractured. The time until the mooring system collapses from the fracture of the first mooring device is called collapse time. Therefore, the probability of the fracture of less than one mooring device in the storm seems to be appropriate as an approximate value of safe side of the failure probability. In the storm, it is possible to consider the condition that mooring force w has exceeded the proof stress r by the low frequency tuning the fracture of the mooring device. The probability in which one mooring device is fractured at least in fixed service life is defined in the following equation.

$$p_d(T) =$$

$$\iint \Pr\left[\bigcup_{k=1}^{N_d} Z_k(t) > 0;0 \le t \le T \mid X = x_i, R = r_k\right] f_X(x_i) f_R(r_k) dx_i dr_k$$

$$Z_k(t) = W_k(t;X) - R_k \qquad (1)$$

X is a random variable about environmental condition such as wind velocity. R is a random variable about proof stress of mooring device. FX(x) and fR(r) are probability density functions. X and R are independent. T is duration time of the environmental condition. Nd is the mooring device number, and k is a consecutive number of mooring device. Pr[|] is the probability in which less than one mooring device is fractured at specific environmental condition and specific proof stress. We shall call this the conditional probability. With the definition of the fracture described in the front, this conditional probability is the probability in which largest mooring force exceeds proof stress in duration time of environmental condition. The annual reliability of the mooring system is given in the following equation, when the distribution of year maximum value was used as probability density function of environmental condition.

$$R_e(T) = 1 - p_d(T) \quad (2)$$

2.2 The estimation method of the failure probability

The distribution of year maximum value of the environmental condition is obtained from the result of measuring the environmental condition of sea area where floating body would be installed in the long term. Though it is described in the back, in this paper, only wind velocity is used as environmental condition. Generally, the measured year maximum wind velocity data are fitted to Weibul-distribution or Gunbell-distribution. The distribution function got by fitting is used as probability density function of environmental condition in equation (1). As a distribution function for year maximum wind velocity, the Gunbell distribution is being recommended by DNV. Since the mooring force is nonlinear, the probability in which the largest mooring force exceeds proof stress is obtained by time domain simulation of the floating body behavior. Largest mooring force data of the Nx set is obtained by carrying out the simulation which corresponds to duration time under the specific environmental condition in the Nx times. Using number Ir of the data as w>r, probability Pr in which the largest mooring reaction exceeds proof stress is given in the following equation.

$$\Pr(x,r) = \frac{I_r}{(N_x + 1)} \quad (3)$$

The proposal of the physical model of the floating body-mooring system for carrying out this time domain simulation is one of the purposes of this paper.

3. The physical model

In this chapter, the physical model for the time domain simulation of the motion in horizontal surface of 5000m floating body moored in the back of the breakwater is proposed. The physical model constructed under following assumptions seems to be appropriate.

1) The environmental condition is the constancy during duration time.
2) The average wind velocity is uniform in considering space.
3) The incident wave is long crested irregular wave.
4) The water depth of considered sea area is uniform.
5) Wave overtopping and diffracted ray are considered in the pier back.
6) It is identical that wave direction of wave overtopping comes with the incident wave.
7) The pier is not damaged.
8) The floating body vertically moves as elastic body.
9) The rigid-body motion in horizontal surface is simulated.

Equation of motion of floating body in horizontal surface is shown in equation (4).

$$\begin{aligned} &\left[M_{ij} + m_{ij}(\infty)\right]\ddot{X}(t) + F_V(\dot{X}) + \\ &\left[\sum_{j=1}^{n} \int_{-\infty}^{t} \dot{x}_j(\tau) L_{ij}(t-\tau)\, d\tau\right] + \\ &F_M(X, \dot{X}) \\ &= F_{wind}(t) + F_1(t) + F_2(t) \end{aligned} \quad (4)$$

X(t) : The displacement vector of floating body.
Mij : Tensor of inertia of floating body.
M(∞): The added mass tensor.
Fv : The viscous damping force vector by the sea water.
L : The memory effect function.
FM : The mooring reaction vector.
Fwind : The wind load vector.
F1 : The first wave force vector.
F2 : Second order wave force vector.

3.1 The environmental condition

Generally, as an environmental condition, wind direction, average wind velocity, wave direction, significant wave height, significant wave period, spectrum form and the space correlation of wind velocity are considered. However, the calculation time for obtaining conditional probability becomes enormous, when there are many parameters of environmental condition to be considered. The environmental condition parameter seems to be appropriate on the handling of being a function of the wind velocity in order to shorten the calculation time. The wave direction is identically with wind direction. By applying the value of the wind velocity to ocean wave predictive equation, significant wave height and significant wave period are obtained. Generally Ⅳ type of Wilson shown in the following equation is well used as ocean wave predictive equation. Fe is the fetch, and U10 is average wind velocity at the 10m height. In addition, it is handled as spectral form and spatial correlation coefficient being approximately constant.

$$H_{1/3} = 0.30\,\frac{U_{10}^{\,2}}{g}\left\{1-\left(1+0.004\sqrt{\frac{gfe}{U_{10}^{\,2}}}\right)^{-2}\right\} \quad (5)$$

$$T_{1/3} = 1.37\cdot 2\pi\,\frac{U_{10}}{g}\left\{1-\left(1+0.008\left(\frac{gfe}{U_{10}^{\,2}}\right)^{\frac{1}{3}}\right)^{-5}\right\} \quad (6)$$

3.2 The estimation of the wave force

The term in proportion to wave height called the linear wave force and the term in proportion to the square of wave height called the slow drift force are included for the wave force.

$$\begin{aligned} F(t) &= F_1(t) + F_2(t) \\ &= \int h_1(\tau)\zeta(t-\tau)d\tau + \\ &\iint h_2(\tau_1,\tau_2)\zeta(t-\tau_1)\zeta(t-\tau_2)d\tau_1 d\tau_2 \end{aligned} \quad (7)$$

F1(t) : The time series of the linear wave force vector.
F2(t) : The time series of the slow drift force vector.
h1 and h2 : The vector of the impulse response function of wave force.
ζ(t) : The time series of surface elevation of incident wave.

The transfer function of slow drift force is obtained as area integral of the secondary order pressure. The secondary order pressure is obtained from all potential under the secondary order. However, it is impossible to obtain the secondary order potential for VLFS at the good accuracy in the current. So, based on the idea of being the order in which the draft is equivalent to wave height, the transfer function of slow drift force is approximately obtained by substituting the relative water-level of the floating body circumference for following equation.

$$H_2(\omega_1,\omega_2) = \frac{1}{2}\rho g \oint \zeta_r(\omega_1)\zeta_r^{*}(\omega_2)\,n\,dl \quad \text{(force)} \quad (8)$$

$$H_2(\omega_1,\omega_2) = \frac{1}{2}\rho g \oint \zeta_r(\omega_1)\zeta_r^{*}(\omega_2)\,r\times n\,dl \quad \text{(moment)}$$

As a calculation method of the relative elevation of water surface, it is possible to use the Ohmatsu's method assuming that the draft of VLFS is the zero. $\zeta r(\omega)$ is a complex amplitude of the relative water-level. * means the conjugation complex number. N is normal direction vector of the side wall, and r is a position vector. Next equation was used in order to shorten the calculation time. S is a spectrum of the incident wave. We call H2 integral QTF. From the similar assumption, the transfer function of linear wave force is approximately obtained using the following equation.

$$H_1(\omega) = \rho d \oint i\omega\phi_d\, n\,dl \quad \text{(force)}$$

$$H_1(\omega) = \rho d \oint i\omega\phi_d\, r\times n\,dl \quad \text{(moment)}$$

(9)

ϕd is the diffraction potential of the first order of the floating body circumference. D is the draft.

3.3 The effect of the breakwater

In the back of the breakwater, wave overtopping and diffracted ray travel. The force by wave overtopping and diffracted ray is assumed independently affecting the floating body to each other. Therefore, the following are required : Transfer function on wave overtopping and transfer function on diffracted ray. The transfer function on wave overtopping is obtained using the relative elevation of water surface around the floating body circumference installed in open sea. The input for this transfer function is a wave with the spectrum transformed using the wave height ratio between wave overtopping and incident wave. By using the relative elevation of water surface around the floating body circumference installed in the back of the breakwater, the transfer function on diffracted ray obtains it. The input is a incident wave. It is the most appropriate to use the following equation proposed by Gohda in order to calculate the wave height ratio between wave overtopping and incident wave. It was confirmed by the experiment.

$$K_T = \begin{cases} \sqrt{0.25\left[1-\sin\frac{\pi}{\alpha}\left(\frac{R_b}{H_I}+\beta\right)\right]^2 + 0.01\left(1-\frac{hm}{h}\right)^2} & \frac{R_b}{H_I} < \alpha-\beta \\ 0.1\left(1-\frac{hm}{h}\right) & \frac{R_b}{H_I} \geq \alpha-\beta \end{cases}$$

$$\alpha = 2.2 \qquad \beta = -0.2 \qquad (10)$$

Rb is a height from the sea surface of the breakwater, HI is the incident wave high, h is a water depth, and hm is a water depth on the mound.

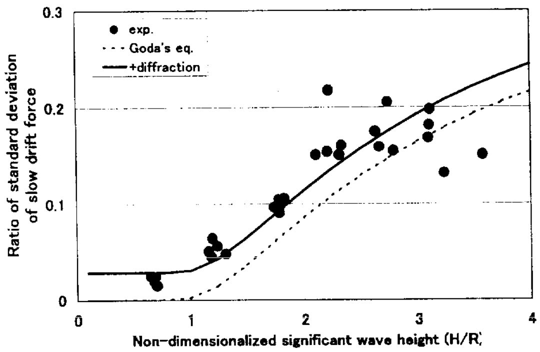

Fig.1 effect of breakwater for slow drift force

Fig.1 shows an example of experimental result on the effect of the breakwater for wave force which affects boxy floating body moored in the back of the breakwater. The floating body has 4.8m and length and 1m width. The length of breakwater was 6.4m. The force was measured in the random wave. The incidence angle is 30deg from breakwater front face. The breakwater is a thin vertical wall made in the even base of the tank. The figure shows the standard deviation of low frequency wave force of the normal direction of the breakwater. This is a ratio between standard deviation in case of the breakwater and one in case of no breakwater. The continuous line appears the square of the equation of Gohda in addition to diffracted ray effect by the method of Ohmatsu.

3.4 Estimation of the wind load

As a wind load, it is necessary to consider pressure drag affecting on side-wall of floating body and frictional drag affecting on deck of floating body. It seems to be appropriate to consider only fluctuation wind velocity in the mainstream direction for the calculation efficiency. The power spectrum of fluctuating wind load considering space correlation of wind velocity is shown in following equation.

$$S_{FF}(f) = \rho_a{}^2 \iint_A C_{di}(f) C_{dj}(f) U^2 \operatorname{Re}(R_{ij}(f)) S(f) dA_i dA_j$$

$$R_{ij}(f) = \exp\left(-\frac{k_1 f |y_i - y_j|}{U}\right) \exp\left(i \frac{k_2 f (x_i - x_j)}{U}\right) \qquad (11)$$

ρa: The air density
U: Average wind velocity
Cd(f): Drag coefficient
DA: The surface area element
S(f): Power spectrum of fluctuating wind velocity
F: The frequency
X: Mainstream direction coordinate value
Y: Mainstream normal direction coordinate value
K1: Space correlation coefficient of the Main-stream normal direction
K2: Space correlation coefficient of the Main-stream direction

It is possible to use the result of wind tunnel experiment by Ohmàtsu et al. as a dràg coefficient. The value of the drag coefficient for friction is 0.0025. The value for the pressure drag is 0.425. It is possible that the spatial correlation coefficient uses k1=7.0 and k2=5.13. They are values generally used for ocean surface wind. With the measuring result on the experiment structure by the Mega-Float technology research association, it is possible to use the spectrum of Ochi-Shin as a fluctuating wind spectrum.

3.5 The hydrodynamic force

As added mass coefficient and radiation damping coefficient, it is possible to use the potential theoretical value of rigid body. This is because the effect of the radiation of the elastic body behavior is included in the wave force. On the viscous damping force for VLFS, the term in proportion to the speed of the floating body is more excellent than the term in proportion to the square of the speed. This is because the

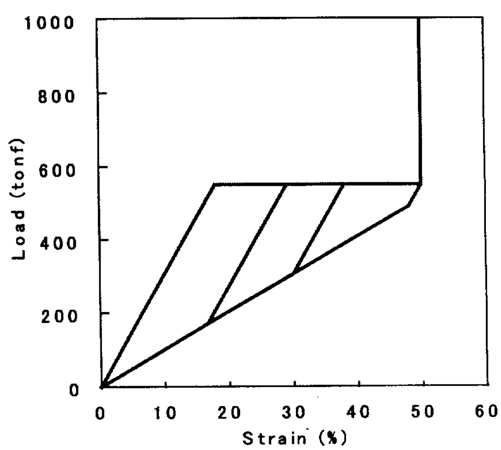

Fig.2 Model of fender

amplitude of the oscillation is small for the scale of the floating body.

The largest displacement magnitude of the fender of mooring device is very smaller than the length of floating body. Though the viscous damping force is function of KC number and Reynold's number, it seems to be possible to handle as a constant value, since the motion amplitude is small. It is possible to use the value by free decay test of the floating body model. Table.1 shows natural frequency and damping factor in the experiment.

3.6 Characteristics of the fender

The model of the fender characteristics is shown in Fig.2.

3.7 Characteristics of the dolphin

The dolphin is assumed as a pile casting type. Characteristics of the dolphin are shown in Fig.3. It is possible to approximate by three straight lines. When the load exceeds yield point, the permanent strain remains except for the load.

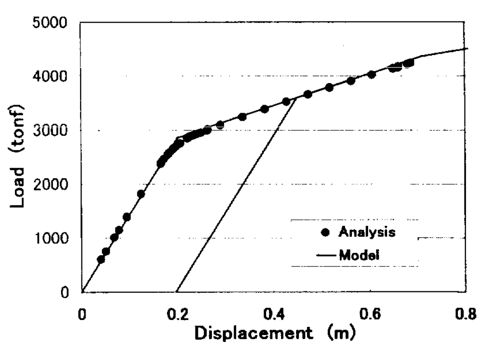

Fig.3 Model of dolphin

4. The example of the analysis

4.1 The object of the analysis

The analysis was carried out under following conditions.

The environmental condition.
  The incidence angle : 60deg.
  The spectral form The wind : Ochi-Shin
                     The wave : JOHNSWAP
  The space correlation coefficient :
      K1=7, K2=5.13.
  Duration time : 3 hours
  The fetch : 20km
The installation condition.
  The height of the breakwater on the sea : 1.8m
  The mound height : 5m
  The breakwater-floating body interval : 200m
  The water depth : 20m
The floating body condition.
  The dimension : 4770×1714×6×2m
The viscous damping coefficient.
  Surge:
  Sway:
  Yaw:
The dolphin.
  The configuration : 20×50 equal spacing
  The design load : 1000tonf
  Proof stress : 2860tonf (yield load)
The fender.
  The steady reaction : 550tonf

4.2 The analytical result

The assumption that the probability density function of proof stress of mooring device in the equation (1) is δ function means that the proof stress is the decision value. This assumption seems to be appropriate, if the quality of the mooring device is sufficiently controlled.
Fig.4 shows conditional probability of the mooring system for the wind velocity. The figure shows two results in the case in which there is a breakwater and case in which there is no one.

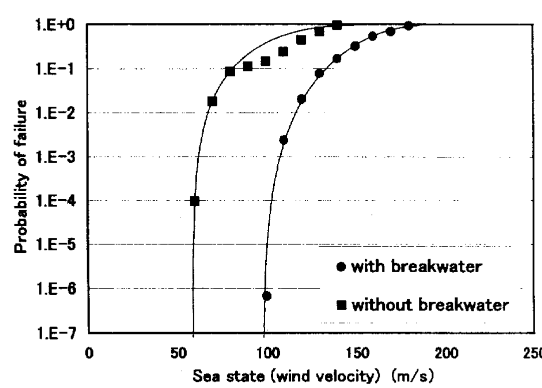

Fig.4 Conditional probability of failure

The continuous line in the figure is a result of fitting analytical result to the Weibul-distribution function. Lowest wind velocity in which the conditional probability becomes more than the zero is 97m/s and 58m/s respectively. The year failure probability is 10-15 and 10-8

respectively. As a distribution function of wind velocity, Gunbell distribution function, to which the measured data over the 26 years in Tokyo Bay is fitted, is used.
Fig.5 shows the extreme value distribution of year maximum wind velocity used for the analysis. Fig.6 shows the failure probability of year for each number of mooring device. The continuous line shows Weibul-distribution function to which analytical result was fitted. There is no method for verifying this result. It seems that this result is rational. It shows that the analysis method shown in this paper is appropriate. It is possible to say that the VLFS with the object of present analysis has been designed under the very high safety factor.

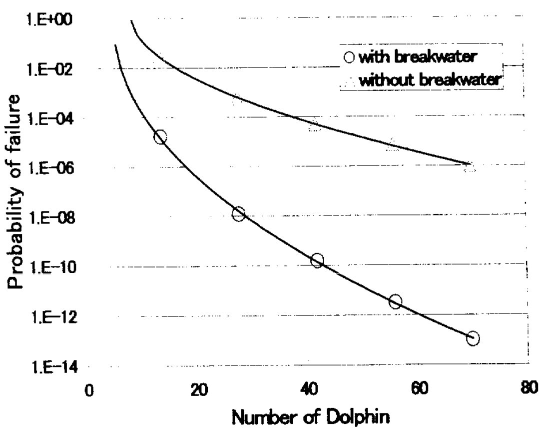

Fig.5 Probability of failure

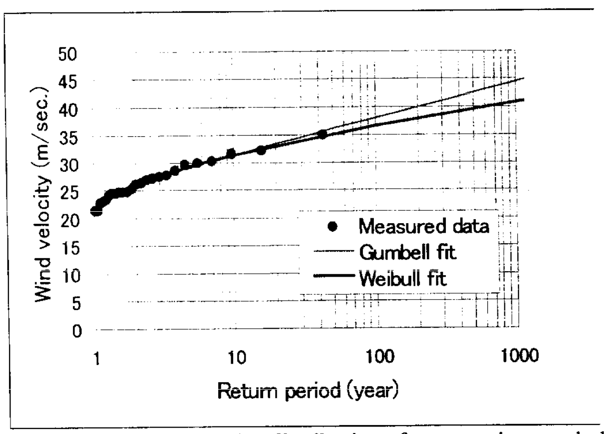

Fig.6 Extreme value distribution of year maximum wind velocity

4.3 The relationship between optimum number and failure probability of the mooring device

In the front stage, it was shown that VLFS with the object of present analysis had been designed under the very high safety factor. So, how meny will be the optimum mooring device number. Here, this problem is examined using the concept called the total cost. It is considered that the sum of risk and construction cost of VLFS is expectation value of the total cost. The risk is a product of failure probability and recovery cost.

$$RI = A(1-R_L) + BN_d + C \cong ALp_d + BN_d + C \quad (12)$$

Ct : The total cost
Pd : The year failure probability
Nd : The mooring device number
A : The recovery cost
B : Construction cost per one mooring device
C : Construction cost except for the mooring Device
L : The service life

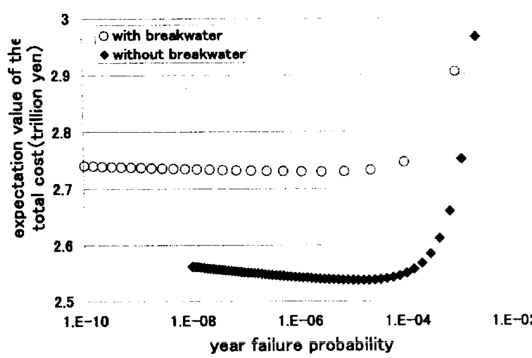

Fig.7 relationship between total cost and failure Probability

The failure probability is decrease function of the mooring device number, and the construction cost is the increase function of it. Therefore, there is the mooring device number which minimizes expectation value of the total cost, when the human damage is very slight. Fig.7 shows the relationship between expectation value of the total cost and year failure probability. The recovery cost was 2 trillion yen, and construction cost of mooring device of one was 400 million yen. Year failure probability in which the total cost was minimized was 10-6, when there was a pier, and it was 10-4, when there was no pier. As year failure probability of public facility, this value seems to be big a little. The failure probability seems to decrease, if criteria considering the human damage are used. In case with the pier and case without the pier, the failure probability in minimizing the total cost is different. It seems to contribute to the setting of the target reliability, if there are the criteria by which the optimum failure probability is fixed regardless of the condition.

5. Conclusion

In this paper, calculation method of the probability in which 5000m VLFS moored in the back of the pier drifted in the storm was proposed. It seems that the analytical result by this method is almost appropriate. Rate of change of the failure probability for the number of mooring device was shown, and the example of the application method was shown.

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